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Washout of Foot and Mouth Disease Virus from the Atmosphere

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INTRODUCTION

There is much evidence both from the laboratory and the field which shows that cattle, sheep, pigs, deer and goats can become infected with airborne Foot and Mouth Disease virus (Fogedby and others, 1960, Smith and Hugh-Jones, 1969, Hugh-Jones and Wright, 1970, Sellers and Gloster, 1980). The atmosphere plays an important role in determining the scale of airborne infection (Gloster and others, 198_).

Smith (1968) in his analysis of the 1952 Cheshire epidemic concluded that 81% of infection occurred within 16 km of a virus source but there were a few cases which involved distances up to 45 km. Hugh-Jones and Wright (1970) concluded that airborne virus was the most likely source of infection for many farms up to 60 km from a known source. They also suspected that other farms at greater distances had been infected by airborne virus. Gloster and others (198-) and Donaldson and others (198-) have demonstrated that airborne infection may occur at distances even greater than these if the passage of the virus has been over the sea. Table 1 gives a summary of the distances involved in these last two studies. The authors showed that infection at such large distances from a virus source requires high levels of virus emission, high virus survival, low virus dispersion and high exposure of susceptible livestock to infected air.

This paper quantifies one aspect of virus survival in the atmosphere: the effect of precipitation upon the virus.

"Washout"

Particles containing Foot and Mouth Disease virus can be removed from the atmosphere by being captured by falling raindrops; this process is referred to as "Washout". When this occurs the downwind concentrations of particles is reduced and the risk of infection is lowered.

"Washout" can be calculated using the following equation (see Appendix 1 for the derivation),

$$\frac{C(x)}{C(o)} = e^{-\left(\frac{3R}{2U}\right) \cdot \frac{\sum V(D) F(D) \eta(D) D^2}{\sum V(D) F(D) D^3} x}$$

where C(x) = concentration at distance x into the rainfall region (m^{-3})

C(o) = concentration at the initial boundary of the rainfall region (m^{-3})

R = Measured rainfall rate ($m\ sec^{-1}$)

U = Wind speed ($m\ sec^{-1}$)

η = Raindrop/particle capture efficiency

D = Raindrop diameter (M)

V (D) = Fall speed of raindrops of diameter D ($m\ sec^{-1}$)

F(D) = Fraction of water comprised of raindrops of diameter D per unit diameter range (m^{-1}).

Solution of "Washout" Equation

The following works have been assumed applicable for the solution of the "Washout" equation:-

1. Raindrop size distribution according to Best (1950).
2. Relationship between infectivity and particle size, Sellers and Parker 1969, see Table 2.

3. For collection efficiencies of lycoperdon spores (mean radius = 2.25 μm, density = 0.73 gm cm^{-3}) and paper mulberry pollen (mean radius = 6.4 μm, density = 1.1 gm cm^{-3}) as a function of raindrop radius(Starr and Mason, 1966) see Figure 1.

Consideration of density and particle size

The densities of the lycoperdon spores and the paper mulberry pollen are not equal to the density of the particles containing virus. It can be shown (Starr, 1966) that under the regime we are interested in the collision efficiency can be expressed as a function of the dimensionless inertial parameter K.

For a raindrop of given size, K & V_f where V_f is the fall speed of the particle.

Now, $V_f \propto r^2\rho$, since the drag is described by Stokes Law,

where ρ = particle density

and r = particle radius

Thus $K \propto r^2\rho$

Particles of differenct sizes thus have the same collision efficiences provided they have the same value of $r^2\rho$.

For lycoperdon spores $r^2\rho = 3.7\ \mu m^2$ gm cm^{-3}. Assuming a density of 1gm cm^{-3} for the particles containing virus we find that $ro' = 1.9\ \mu m$; for paper mulberry pollen $r^2\rho = 45.1\ \mu m^2$ gm cm^{-3} so that $ro'' = 6.7\ \mu m$, where ro' and ro'' are the radii of particles having the same collision efficiencies as the lycoperdon and paper mulberry respectively.

The equation was solved for two particles of radii ro' and ro'' using the collection efficiencies in Figure 1. Figure 2 and 3 give the distance x at which various amounts of "Washout" have occurred as a function of rainfall rate, R, for the two particle sizes. The upper x-axis is used for U = 10 m sec^{-1} and the lower one for U = 5 m sec^{-1}. Other windspeeds can be accommodated by changing the scaling of the x-axis linearly.

Example: with $U = 10$ m sec^{-1}

and $R = 2$ mm hr^{-1}

50% of particles containing virus 1.9 μm radius will be washed out in 100 km

and 50% of particles containing virus 6.7 μm radius will be washed out in 12 km.

Application of Calculations to 1981 outbreak of Foot and Mouth Disease

Donaldson and others (198-) showed that infection of animals on the Isle of Wight was most probably caused by airborne virus, emitted 250 km away in Brittany on either 7th or 10th March 1981. On both of these occasions the virus would have encountered precipitation for part of the 8 hour journey from France to England. An approximate value for the "Washout" can be found using Figures 2 and 3 by assuming a windspeed $U = 10$ m sec^{-1}, a constant rainfall rate $R = 0.3$ mm hr^{-1} for the whole 250 km journey. It would appear that $\sim$ 50% of particles containing virus of 1.9 μm radius and 90% of particles of 6.7 μm radius would have been washed out of the atmosphere. According to the analysis in this paper a significant amount of the virus emitted in France would have escaped the "Washout" process and hence would be capable of causing infection on the English coast.

Final Observations

Two points emerge from these calculations. Firstly, although the smaller particles containing virus appear to be less infective than the larger ones (Sellers and Parker, 1969) they are more likely to survive the "Washout" process and hence be capable of causing infection. Secondly, the size of the particles to which the virus is attached and its subsequent behaviour in the air, e.g. evaporation may well determine the likelihood of subsequent infection.

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Any comments or suggestions on this paper should be referred to the authors.

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Bracknell

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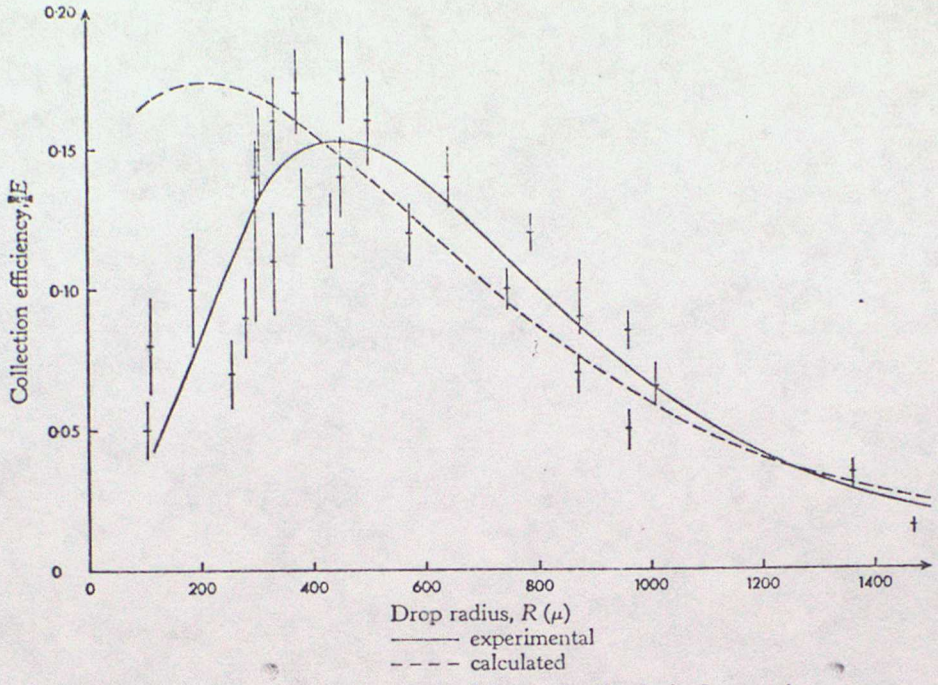
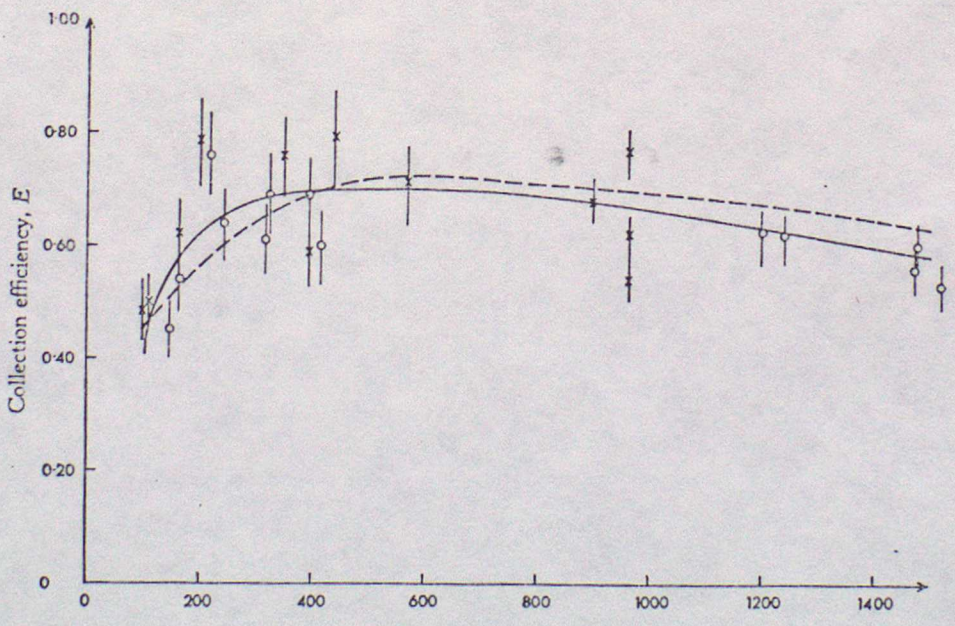
FIG. 1



Collection efficiencies, E, of drops of radius R, for Lycoperdon spores.



. Collection efficiencies, E, of drops of radius R for particles of Paper Mulberry pollen.

FIGURE 2. "WASHOUT" assuming virus particles have a mean radius of 1.9 μm.

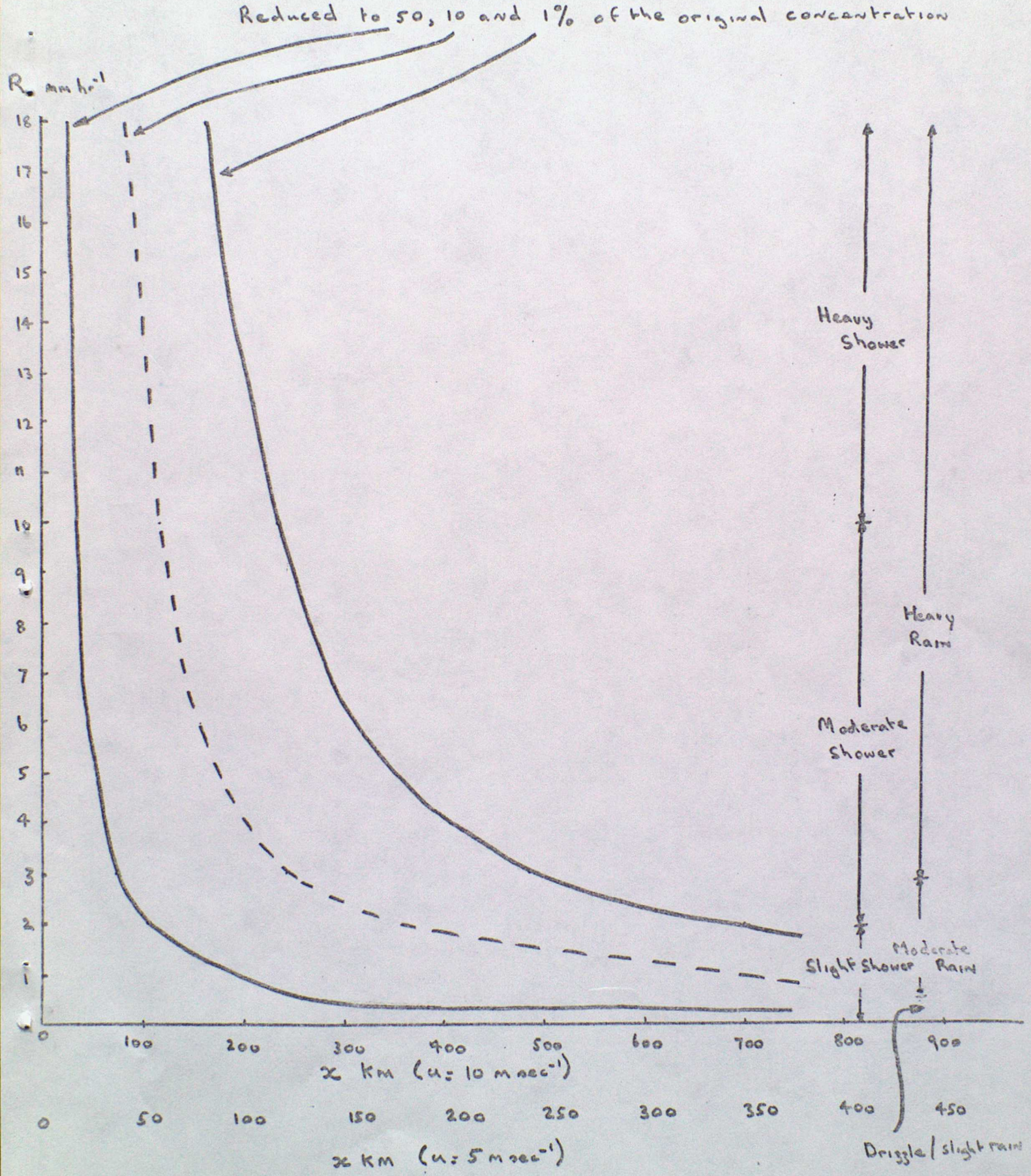


FIGURE 3. "WASHOUT" assuming virus particles have a mean radius of 6.7 μm.

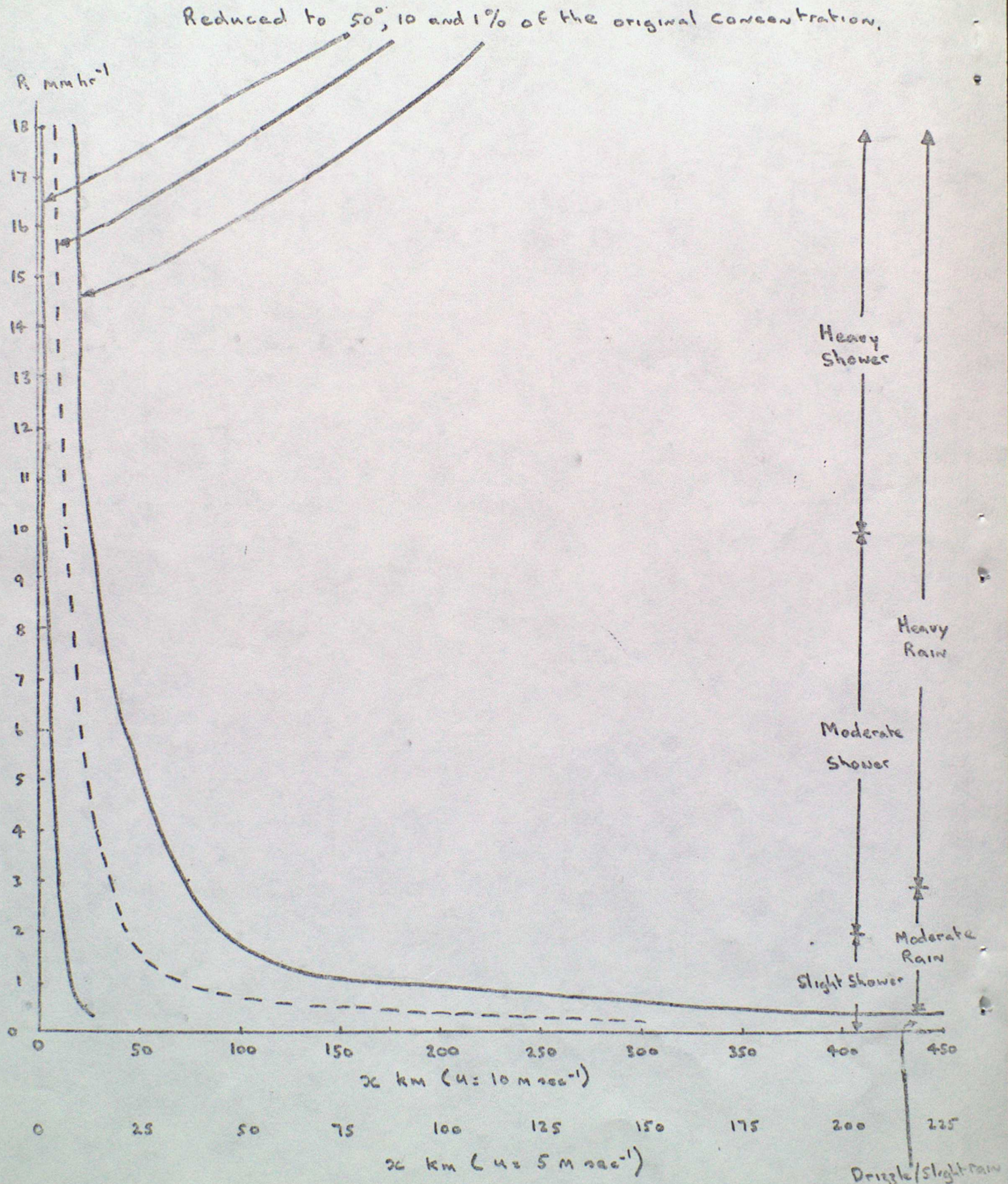


TABLE 1

Summary of the findings of Gloster and others (198_) and Donaldson and others (198_)

OUTBREAK DETAILS	DISTANCE (km)
Denmark 1966	30
Denmark/Sweden 1966	100
France/Channel Islands 1974	105
France/Channel Islands 1981	100
France/England (Isle of Wight) 1981	250

TABLE 2

Infectivity, %	Particle radius (u)
65–71	> 3
19–24	1.5–3
10–11	< 1.5

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APPENDIX I

Let N = number of raindrops per unit volume with diameter $> D_o$

R = rainfall rate

(D_o is chosen so that the contribution to the rainfall, R, by drops of diameter $< D_o$ is negligible).

$v(D)$ = fall speed of raindrops of diameter D

$Nn(D)\,dD$ = number of raindrops per unit volume with diameters in the range dD about D (the function $n(D)$ is obtained in Appendix II)

Now,

$$R = N\int_{D_o}^{\infty} n(D)\, v(D)\, 4\pi/3\, (D/2)^3\, dD$$

or

$$N = \frac{R}{\pi/6 \int_{D_o}^{\infty} n(D)\, v(D)\, D^3\, dD} = \frac{6R/\pi}{I} \qquad \text{(i)}$$

Consider the raindrops with diameters in the range dD about D. Each raindrop sweeps a volume = $\pi (D/2)^2\, v(D)$ in unit time. Total number of such drops per unit volume = $\{N n(D)\, dD\}$. Thus, fraction of any given volume swept out per unit time is,

$$F(D) = \{N n(D)\, dD\}\, \pi (D/2)^2\, v(D)$$

Using equation (i),

$$F(D) = \frac{3R}{2I}\, v(D)\, n(D)\, D^2\, dD \qquad \text{(ii)}$$

Number of particles containing virus swept out per unit volume per unit time by these raindrops is

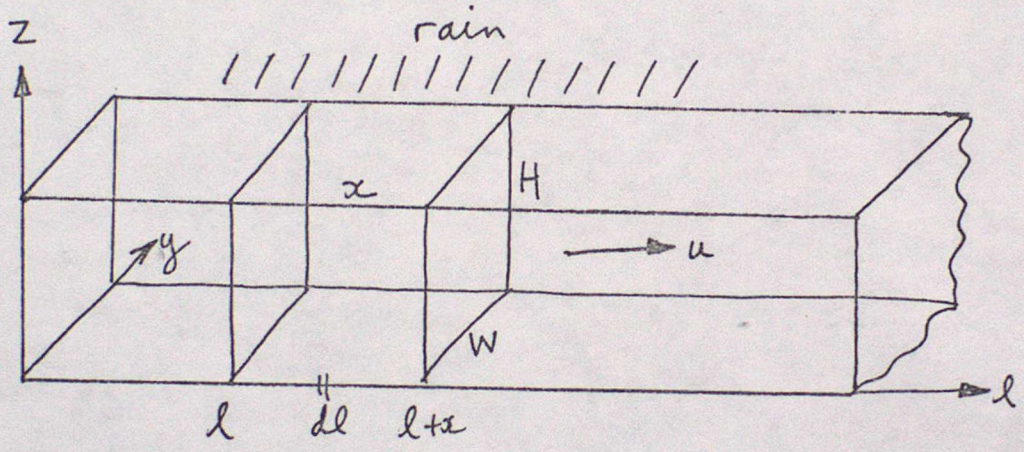
$$M(D) = \eta(D)\, c\, F(D)$$

where $\eta(D)$ = capture efficiency

and C = No. of particles per unit volume

using equation (ii),

$$M(D) = \frac{3Rc}{2I}\left\{V(D)n(D)D^2\eta(D)dD\right\} \quad \text{(iii)}$$



$c(l)$ = concentration of particles containing virus a distance l into the rainfall region.

In unit time,

No. of particles passing through right face = $c(l+dl)\,wHu$

No. of particles passing through left face = $c(l)\,wHu$

No. washed out within dl = $wHu\left[c(l)-c(l+dl)\right]$

$= -wHu\,dl\,\partial c/\partial l$

But, no. washed out within dl = $M(D)\{wH\,dl\}$

Thus, $-wHu\,dl\,\partial c/\partial l = wH\,dl\,M(D)$

Using (iii), $\partial c/\partial l = -M(D)/u = -3Rc/2uI \left\{ v(D)n(D)D^2\eta(D)dD \right\}$

Considering the full spectrum of raindrops,

$$\frac{dc}{c} = -\frac{3R\,dl}{2uI}\int_{D_0}^{\infty} v(D)n(D)D^2\eta(D)dD$$

Integrating, $$\int_{c(0)}^{c(x)} dc/c = -\frac{3R}{2uI}\int_{D_0}^{\infty} v(D)n(D)D^2\eta(D)dD \int_0^x dl$$

$$\ln\left[c(x)/c(0)\right] = -3Rx/2uI \int_{D_0}^{\infty} ---- dD$$

$$c(x)/c(0) = e^{-\frac{3Rx}{2uI}\int ---- dD} \qquad \text{---------- (iv)}$$

Rather than working with integrals we do a summation. Considering the exponent, we write -

$$\frac{-3Rx\int_{D_0}^{\infty} v(D)n(D)D^2\eta(D)dD}{2u\int_{D_0}^{\infty} v(D)n(D)D^3 dD} \simeq -\frac{3Rx}{2u}\frac{\sum_{D_i=D_0}^{D'} v(D_i)n(D_i)\eta(D_i)D_i^2(\Delta D)}{\sum_{D_i=D_0}^{D'} v(D_i)n(D_i)D_i^3(\Delta D)}$$

where D' is such that the contribution to the summation by terms with $D > D'$ is negligible.

$\Delta D = 0.25$ mm

$D_0 = 100\mu = 0.1$mm

$D' \sim$ a few mm

The exponent can be simplified by using $f(D)$ rather than $n(D)$ (see Appendix II).

We can then write -

$$\frac{c(x)}{c(0)} = e^{-\left(\frac{3Rx}{2u}\right)\cdot\frac{\sum_i v(D_i)\eta(D_i)f(D_i)/D_i}{\sum_i v(D_i)f(D_i)}}$$

APPENDIX II

From Best (1950), we find, $1 - F = e^{-(D/a)^n}$

where $n = 2.25$

D = diameter of raindrops in mm

$a = 1.3 R^{0.232}$

R = rainfall rate in mm/hour

$Q(D) \equiv 1 - F$ = fraction of water comprised of drops with diameter $> D$

Let $f(D)dD$ = fraction of water comprised of raindrops with diameters in the range dD about D

$$f(D)dD = Q(D) - Q(D+dD)$$

But $dQ/dD = \dfrac{Q(D+dD) - Q(D)}{dD}$

$$\therefore f(D) = -dQ/dD$$

$$= -d/dD\, e^{-(D/a)^n}$$

$$f(D) = \frac{n}{a^n} D^{n-1} e^{-(D/a)^n}$$

(units: mm^{-1}, see Fig 1 for a set of curves of $f(D)$ vs D)

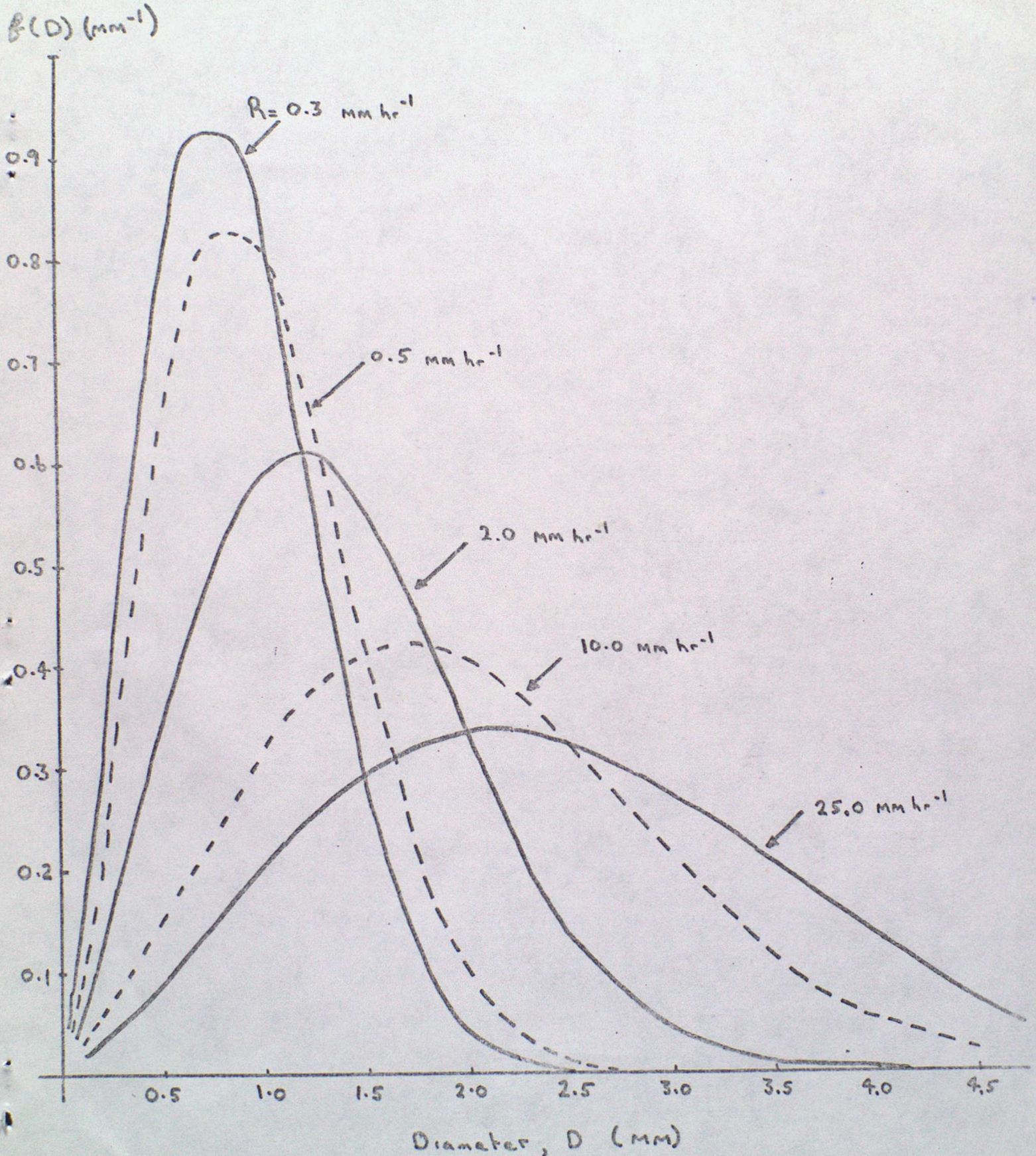
$$\left(\text{clearly } \int_0^\infty f(D)dD = 1 \right)$$

If $n(D)dD$ is the fraction of raindrops with diameters in the range dD about D then,

$$n(D)dD\left(4\pi/3\right)(D/2)^3 = f(D)dD$$

$$\therefore (\pi/6)n(D)D^3 = f(D)$$

FIGURE 1.


f(D) (mm⁻¹)
R = 0.3 mm hr⁻¹
0.5 mm hr⁻¹
2.0 mm hr⁻¹
10.0 mm hr⁻¹
25.0 mm hr⁻¹
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Diameter, D (mm)